

New Results on R Aquarii

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Abstract.

The first results on new optical data for R Aquarii¹ are presented. The morphology and kinematics of the nebula, based on data obtained with the NTT from 1991 to 2000, are discussed. Physical parameters of the outer nebula and the knotty jet are derived using spectra obtained with the INT in 2001. From the analysis of all these data we propose that the spectacular knotty inner structure of R Aqr could result from the interaction of a highly collimated pulsating young jet with the older hourglass inner nebula.

1. The R Aqr System

Since the work of Solf & Ulrich (1985), it has been well known that the large-scale optical structure of R Aqr consists of two binary (hourglass-like) shells formed by two successive explosions of the system, and that these shells share the same major axis. The inclination of the polar axis with respect to the line of sight is $\sim 70^\circ$ (Hollis et al. 1999). The expansion of both shells in the polar direction is about six times faster than that in the equatorial direction, their polar expansion being 32 km s^{-1} and 55 km s^{-1} , implying kinematical ages of 185 yr and 640 yr, for the inner and outer shells, respectively (Solf & Ulrich 1985). On smaller scales, R Aqr has a string of knots whose first detection occurred in the late 1970s (the NE jet: knots A, B and D in Fig. 3) and 1980s (the SW jet: knot A' in Fig. 3; see Paresce, Burrows, & Horne 1988). Hollis et al. (1991) derived the kinematical age of the outermost NE knot as being around 90 yr, implying that this jet is younger than the inner large-scale shell. Although being around 90 yr old, the jet was not observed before 1977 (NE knots, Wallerstein & Greenstein 1980; Herbig 1980) nor before 1988 (SW knot, Hollis, Wagner & Oliverson 1990). Its sudden detection, with some brightening enhancement, suggests its impact with the environments (the inner shell).

¹Based on observations obtained with the 2.5m INT, the 2.5m NOT and the 3.5m NTT.

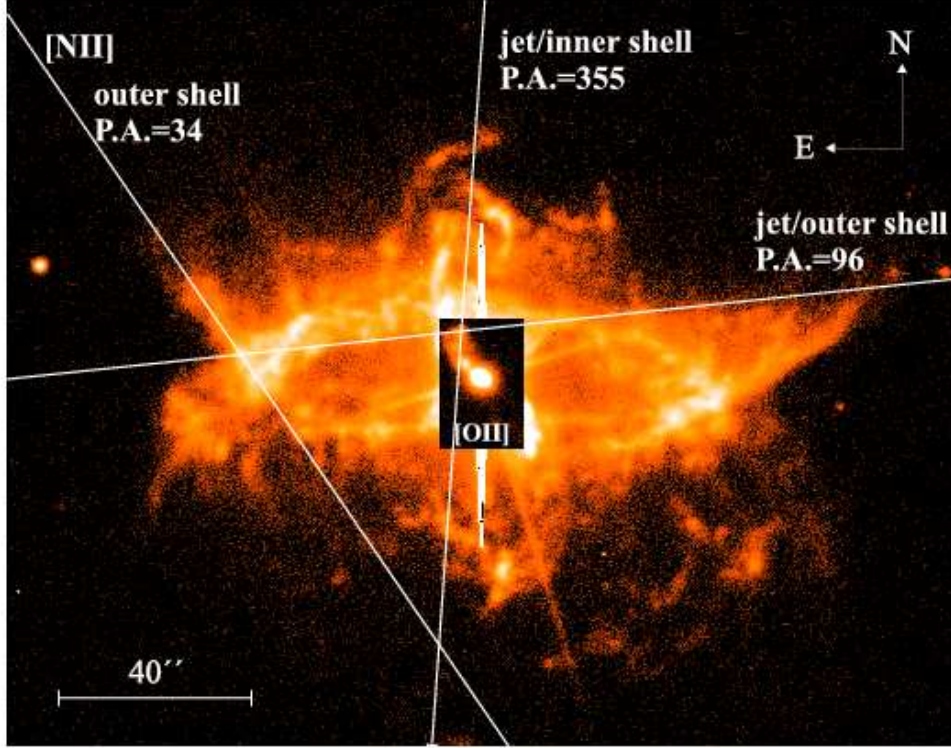


Figure 1. The $[\text{N II}]$ image of R Aqr large-scale shells, with the $[\text{O III}]$ jet image in the center. The vertical bright “bar” is caused by the saturation in the central region. The white lines show schematically the slit positions for the INT + IDS spectra (see text).

2. Physical Parameters and Excitation of Outer Shell and Inner Jet

We derived the physical parameters and excitation mechanisms for the different features of R Aqr, based on the 3.11 \AA/pix , $0.7''/\text{pix}$ long-slit spectra, obtained with the INT + IDS in August, 2001. Fig. 1 shows the positions of our three slits superposed on the image of the large and small-scale features of R Aqr. We choose these three PAs in order to study the properties of the jet’s knots and inner shell ($3.8'' \text{ E}$, $8.4'' \text{ N}$, $\text{P.A.} = 355^\circ$), those of the outermost jet’s knot and outer shell ($3.8'' \text{ E}$, $8.4'' \text{ N}$, $\text{P.A.} = 96^\circ$) and of the brightest regions of the outer shell ($42.5'' \text{ E}$, $2.1'' \text{ N}$, $\text{P.A.} = 34^\circ$).

Electron temperatures and densities, $N_e[\text{S II}]$, were estimated at many positions along the three slits. Portions of the outer shells have, on average, $T_e[\text{N II}] \cong 1.4 \times 10^4 \text{ K}$ ($T_e[\text{O III}] \cong 1.8 \times 10^4 \text{ K}$). The jet’s knots have $T_e[\text{N II}] \cong 1.3 \times 10^4 \text{ K}$ and $T_e[\text{O III}] \cong 1.9 \times 10^4 \text{ K}$, implying very similar T_e for the outer shell and inner jets. Densities, on the other hand, vary by large amounts along each slit. The NE portion of the outer shell, crossed by two slits, has a $N_e[\text{S II}] \cong 230 \text{ cm}^{-3}$. The roughly opposite position of the outer shell, its NW side, shows approximately the same density, $\sim 200 \text{ cm}^{-3}$. At the position of Knot D, in which the $\text{P.A.} =$

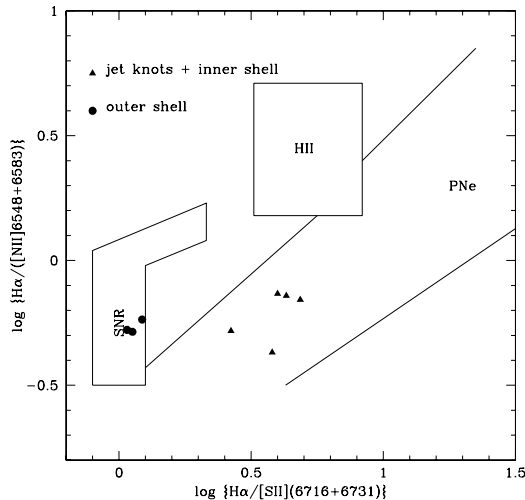


Figure 2. Diagnostic diagram with $[\text{O III}]/\text{H}\alpha$ versus $[\text{S II}]/\text{H}\alpha$ showing different features of R Aqr (from Cantó 1981).

96° as well as P.A. = 355° are centred, densities are higher than those that can be safely determined by the $[\text{S II}]$ lines, $N_e[\text{S II}] > 10^4 \text{ cm}^{-3}$. Finally, electron densities of the inner knots are around 600 cm^{-3} , and that of the inner shell cut by our slit at the Northern as well at Southern sides of the system (P.A. = 355°) is $\sim 620 \text{ cm}^{-3}$. At the positions where other estimations are available, they are in general agreement with ours (Solf & Ulrich 1985; Kafatos, Michalitsianos, & Hollis 1986; Hollis et al. 1991; Meier & Kafatos 1995).

The high $T_e[\text{O III}]$ ($\sim 1.8 \times 10^4 \text{ K}$) measured for the system is indicative of mild shock excitation. With Fig. 2 we investigate the excitation of many regions in R Aqr. We see that those regions which are mainly excited by shocks are part of the outer shell (circles). On the other hand, all the other features (triangles) lie in the zone of the diagram where photoionization by the central star is the main excitation process (the PNe zone). Note, however, that PNe used to define the PNe “zone” are not spatially resolved, at variance with our points for R Aqr in Fig. 2. Because of that it is possible that some shock excitation could be contaminating features placed in this zone of the diagram.

2.1. Morphological and Kinematical Jet Evolution

From the images in Fig. 3 (1991 July, with the NTT + EMMI, $0.35''/\text{pix}$; and 1997 July with the NOT + ALFOSC; $0.19''/\text{pix}$), and previous works, the morphological evolution of the jet is the following: Knot B was the brightest one up to 1985 (Paresce et al. 1988); Knot B and Knot D were as bright as Knot A in 1986 (Solf 1992); Knot D was hardly brighter than Knot B in 1991 (Fig. 3); and finally, Knot A and Knot A' were the brightest in 1997 (Fig. 3). We also note that the knotty features evolved from round and compact knots in 1991 to more elongated and diffuse ones in 1997. From the morphological changes of Fig. 3, and references cited above, it is evident that the R Aqr jet evolves over timescales smaller than 5 yr. However, caution should be taken when comparing

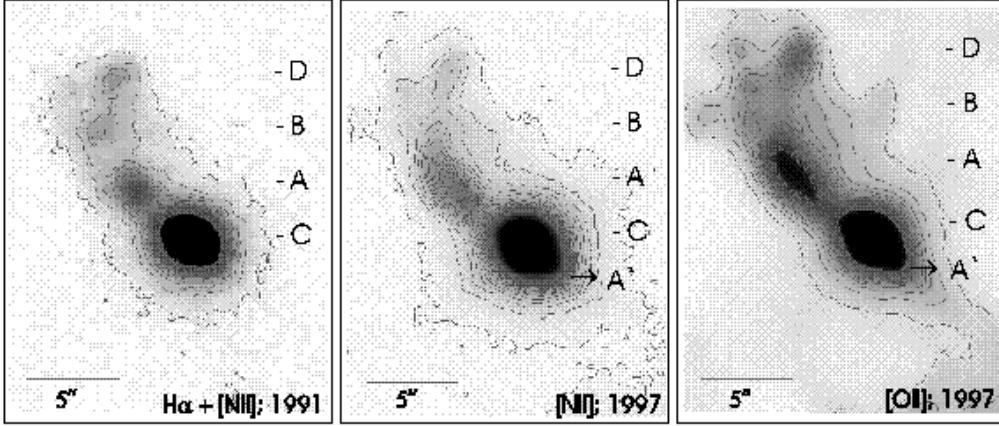


Figure 3. Images of the R Aqr inner jet. *Left to right*; The broad $H\alpha$, and narrow $[N II]$ and $[O II]$ filters images in 1991, 1997, and 1997, respectively. Note the horizontal marks on the right side of each panel that define the position of the Knots A, B and D (NE jet components); C (the central source continuum) and A' (the SW jet).

images obtained in different epochs and with different instrumentations, filters and seeings.

From the high resolution spectra (1999 January, see Navarro et al., this volume, p. 000), one of them crossing the Knot D, we note that in 1999 Knot D was no longer the brightest knot, since it was not detected in our spectrum, at variance with knots A and A'. Therefore, if present in 1999, Knot D came to be less bright than the innermost ones Knot A (NE jet) and Knot A' (SW jet).

2.2. On the Controversial Origin of the Knotty Jet

Solf & Ulrich (1985) and Solf (1992) first suggested that the string of knots (A to D) is formed by fossil condensations of the inner (190 yr) shell, which are being illuminated by the impact of a well collimated jet. However, Hollis and coworkers (Hollis et al. 1991, 1997, 1999) argued that such a group of knots are bright clumps of a highly collimated jet that interacts with the inner nebulosity. In another words, these two approaches differ in that the former sees the knots as part of the inner shell and the latter as part of the jet. Finally, since Hollis et al. (1991) determined the age of the outermost jet's knot (Knot D) as being ~ 90 yr, it became clear that knots cannot be inhomogeneities of the inner shell, which is considerably older than Knot D (see Section 1).

The present results are much more in agreement with the idea that the string of knots in the inner regions of R Aqr is part of a knotty jet, because of the brightness' evolution of the knots (discussed in the previous section), indicative of a precessing jet with pulsation. Putting together the latter, the new results on the kinematics of the knotty jet (see also Navarro et al, this volume, p. 000) and the jet's age (Hollis et al. 1991), we propose that the knotty inner structure of R Aqr is the result of the interaction of a highly collimated pulsating young jet with the older hourglass inner nebula. To check further this idea a more robust comparison of images (probably compiling data from many authors in order to achieve a well covered set of filters and epochs) is desirable, as well

as more deeply investigating if the emission of the knots is partially excited by shocks, which would prove their interaction with the surrounds.

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Discussion

Balick: In R Aqr we see a precessing string of knots close to the nucleus. In He 2-104 (which is about ten times more distant), we see an hourglass nebula in the inner part of the object. Do you believe that there is an evolutionary connection? Can the precessing string of outflowing knots eventually form a larger hourglass, like that in He 2-104 or MyCa18?

Gonçalves: Considering that we have precession in the very inner R Aqr jet, we might think about an evolution in this system that would result in structures like the hourglass shells of, for instance, He 2-104. However, if we compare the R Aqr jet with that of CH Cyg, we would say that such an evolution is not that clear. In CH Cyg, the radio jet observed in 1985 (Taylor et al. 1986) disappeared about fifteen years later (Corradi et al. 2001); in the optical emission, its remnant is what we see now as an optical nebulosity, which appears in the PV diagrams as having a more or less hourglass structure. But note that the latter is much more of a speculation than a clear result based on the data.

Viotti: Also in connection with the possible origin of the soft X-ray emission of R Aqr detected by *EXOSAT*, it would be desirable to investigate the ionization in different parts of the nebula, for instance by looking at the $\text{He}^{++}/\text{He}^+$ emission lines.

Gonçalves: Only the spectra of the jet present these lines and they are fainter than, for instance, the [O III], [S II], [N II] lines, which I have used to derive the main excitation mechanism of each region (Phillips & Cuesta 1999; Cantó 1981; etc.).